SNAP-1: A Low Cost Modular COTS-Based Nano-Satellite – Design, Construction, Launch and Early Operations Phase

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Abstract

Driven by the personal computer and personal communications markets, commercial-off-the-shelf (COTS) microelectronic systems have advanced considerably in the last few years, making it now feasible to construct highly capable "nano-satellites" (i.e. sub-10 kg satellites) to provide cost-effective and rapid-response, orbiting-test-vehicles for advanced space missions and technologies. The UK's first nano-satellite: SNAP-1 - designed and built by Surrey Space Centre (SSC) and Surrey Satellite Technology Ltd (SSTL) staff - is an example of such a test-vehicle, in this case, built with the primary objective of demonstrating that a sophisticated, fully agile nano-satellite can be constructed rapidly, and at very low cost, using an extension of the modular-COTS-based design philosophy pioneered by Surrey for its micro-satellites.

SNAP-1 was successfully lofted into orbit on June 28th 2000 from the Plesetsk cosmodrome on-board a Russian Cosmos launch vehicle. It flew alongside a Russian COSPAS-SARSAT satellite called Nadezhda, and an SSTL-built Chinese micro-satellite, called Tsinghua-1.

The first year of operations has been highly successful, with SNAP-1 becoming the first nano-satellite to have demonstrated full attitude and orbit control via its miniature momentum-wheel-based attitude control system and its butane-propellant-based propulsion system.

This paper discusses Surrey's design philosophy for COTS-based nano-satellites, and reviews the initial results of the SNAP-1 mission.

Introduction

Over the past decade interest has grown in potentialities of nano-satellites (i.e. sub-10 kg satellites).

Advances in commercial-off-the-shelf (COTS) microelectronics and miniature/micro-mechanical systems mean that the capabilities of nano-satellites can now easily match or exceed those of typical micro-satellites of the last decade.

The small size and low mass of nano-satellites makes it feasible to launch several (perhaps many) together, effectively reducing the launch cost per vehicle. This opens up possibilities for new mission scenarios where clusters or constellations of "nano" spacecraft can synthesise functions previously requiring much larger space vehicles. Indeed, it is our contention that using a COTS-based approach, combined with a simplified, modular, spacecraft architecture, it is possible to significantly decrease the time-to-completion, and substantially reduce costs, for some space mission scenarios.

The Surrey Nano-satellite Applications Programme (SNAP) was conceived in the mid-1990's as a means of demonstrating a low cost COTS-based nano-satellite platform for both technological and educational use. Work began as a series of design studies, and systems prototypes carried out in the context of undergraduate and post-graduate student projects within the Surrey Space Centre (SSC). However, in 1999, the programme was adopted by Surrey Satellite Technology Ltd (SSTL) as part of its research and development activities [1]. This resulted in the final definition of the SNAP-1 mission, which was formally began in October 1999, when a launch opportunity (initially set for April 2000) was identified alongside the Chinese Tsinghua-1 micro-satellite – itself built by SSTL.

As it turned out, the launch slipped to June 2000, and the fully tested SNAP-1 spacecraft was delivered in early May 2000 – i.e. the total time from definition-to-orbit (for a brand new spacecraft design) was just nine months!

To realise the project, a small team of Space Centre academics and SSTL engineers was put together under the leadership of Dr. Underwood as Chief Architect and co-Project Manager, Mr. Salvignol as Principal Project Manager and Dr. Richardson as Chief Mechanical Engineer. The team was supported in full by SSTL's satellite manufacturing infrastructure – all co-located in the Space Centre, at the Guildford campus.

The objectives set for the mission were to develop and prove a modular COTS-based nano-satellite bus, and in the process, evaluate new manufacturing techniques and technologies. The spacecraft was also to be used to obtain images of Tsinghua-1 during its deployment, and to demonstrate the systems required for future nano-satellite constellations: i.e. 3-axis attitude control, precise GPS-based orbit determination, and automated orbital manoeuvres.

Finally, if propellant reserves allowed, SNAP-1 was to rendezvous with Tsinghua-1 and carry out "formation-flying" manoeuvres.

Design Philosophy

The potential benefits of nano-satellites lie in significantly lowering mission costs and reducing the time to completion for individual spacecraft. This is, of course, essentially what was foreseen by Surrey more than twenty years ago in the context of its micro-satellites. Thus, Surrey's approach to nano-satellite design can be regarded as a natural extension of the COTS-based "modular" design approach that it has applied so successfully to micro-satellites since 1979. The approach can be encapsulated in a few key principles, namely:

- to facilitate concurrent design;
- to make it modular, and to standardise both the electrical and mechanical interfaces;
- to make it easy to assemble and test;
- to use COTS technologies, but to make the design robust;
- and above all - to keep it simple!

For SNAP-1, a simple standard electrical interface was prescribed for each module, consisting of regulated 5V and raw battery (V_{batt} ~7.2V) power connections, with a single bi-directional Controller-Area-Network (CAN) bus for data transfer. These connections are provided via a 9-way D-type connector, which is standard to all modules.

This simplified testing and harness design. Indeed, all the SNAP-1 modules (except the power system) could be powered and tested using just the standard 9-way connector. In addition to this, a single 44-way D-type connector was also allowed for each module to provide for specific point-to-point connections (where absolutely necessary).

All modules, except the on-board computer (OBC) and machine vision system (MVS) contain a standard 8-bit CAN-micro-controller (the Siemens C515), which provides telemetry and telecommand operations, data transfer and a degree of sub-system autonomy.

The OBC and MVS systems are based around 32-bit StrongARM SA1100 RISC processors, to which we have added external CAN interfaces operated via the StrongARM's in-built SPI interface.

A standard module box mechanical format was also defined at the beginning of the SNAP programme, thus, every module on SNAP-1 has the same external dimensions, sized approximately to house a standard "Eurocard" printed circuit board (160 mm x 100 mm, with ~13 mm of useable depth).

This approach allowed the mechanics, avionics and payload design to occur in parallel, and largely in isolation. It also allowed procurement to start at a very early stage in the programme.

Figure 1 shows the top view of the interior of the SNAP-1 spacecraft. It is constructed from three sets of three electronic module boxes, connected together to form a triangular structure. The small size of the spacecraft is apparent from the scale of the hand in the picture.

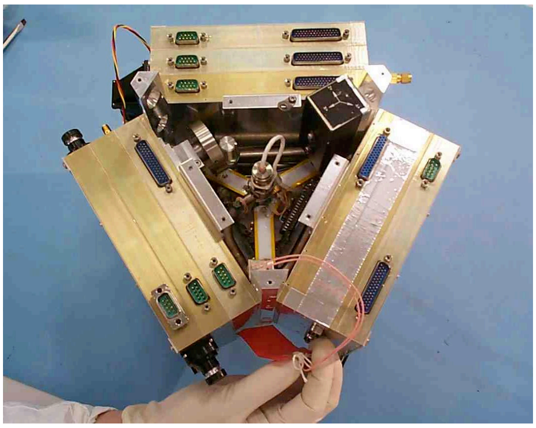

Fig. 1: SNAP-1 Internal Structure

Avionics

Power System

The SNAP-1 spacecraft generates power through four body mounted solar panels, each populated with 20% efficient GaAs cells producing, nominally 0.5A per panel at 12V (i.e. ~6W). Because of the mechanical configuration of the satellite (see Fig. 2), the total orbit average power available is also approximately 6W. However, the minimum *required* bus power is only 650 mW (which represents only the receiver and power system being on), thus, under nominal power conditions these systems, together with the OBC, and the attitude control system (ACS) can be in continuous use.

In addition, the GPS navigation system, payloads and transmitter can be activated periodically as required.

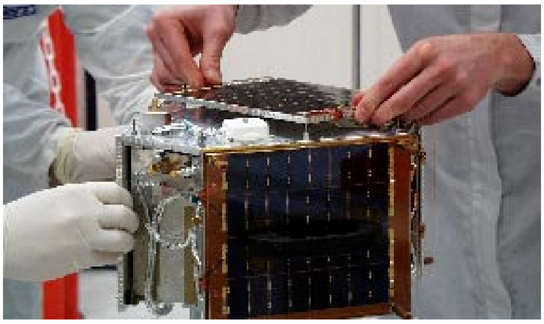

Fig. 2: SNAP-1 Solar Panels (4 in Total)

Solar array temperatures, voltages and currents are measured by the power system via its in-built CAN micro-controller. Each solar panel has it own independent battery charge regulator (BCR) which implements maximum-power-point (MPP) tracking in hardware. This approach gives maximum power transfer efficiency and flexibility for future panel configurations.

The BCRs charge a single 10 Whr battery consisting of six 'A' sized SANYO KR-1400AE Cadnica cells series-linked to give a nominal 7.2V (V_{batt}). The total mass of the battery pack is 270g, which gives a relatively high energy density of 37 Whr/kg. Overcharging of the battery is prevented using a temperature compensated end-of-charge voltage trigger to switch the BCRs into a trickle-charging mode.

The power conditioning module (PCM) provides a regulated 5V supply, and an unregulated 12V supply for the spacecraft systems. The maximum total current that can be safely drawn from the PCM is ~3A. In total, the battery can sustain up to ~10A (i.e. ~60W) output for a few minutes. This feature was designed to allow future SNAPs to support high-power-demand payloads or thrusters.

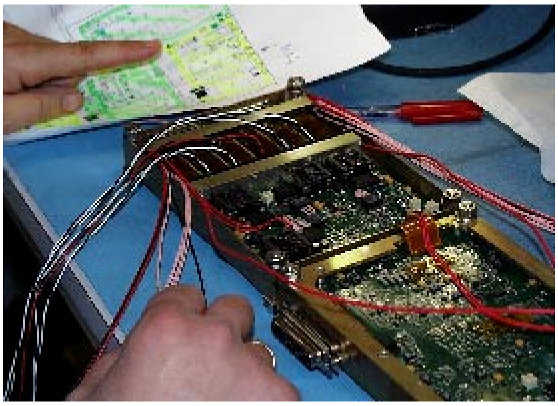

Fig. 3: The SNAP-1 Power System (Battery, BCR/PCM/PDM)

The power distribution module (PDM) uses miniaturised low R_{DS}-on FET power switches, which are based on the design used in current SSTL micro-satellites. There are 8 switched 5V lines and 8 switched V_{batt} lines, and a single switched 12V line. All switches provide over-current protection (for example to help protect systems in case of single-event latch-up). Essential systems (e.g. the receiver) are connected directly via a fuse (for ground testing).

The complete power system (including battery) is housed in a standard double module (see Fig. 3).

VHF Receiver

The VHF receiver (Fig. 4) is a single frequency crystal-controlled device, operating at a selected frequency in the 140-150 MHz band. The uplink modulation scheme is frequency-shift-keying (FSK) which ensures that the receiver is compatible existing SSTL micro-satellite ground-station uplink facilities.

The nominal uplink data rate is 9600 bps, which ensures that the signal bandwidth remains within the limits specified for amateur radio communications. For non-amateur use, the receiver can be operated up to a maximum of 76.8 kbps. The fixed frequency design minimizes the tuning requires and simplifies system set-up and testing

Fig.4: SNAP-1 VHF Uplink Receiver

In the primary mode of operation, digital data are up-linked to the spacecraft asynchronously using a CAN-based packet communications protocol.

The receiver's CAN-micro-processor passes these packets on to the internal CAN bus and also directly on to the OBC (to facilitate software uploading). This direct link to the OBC allows program code and data to be uploaded efficiently via the OBC's "bootloader".

The receiver also sends "received data" and "received data-clock" signals to the OBC, which allow synchronous communications to be supported. This provides compatibility with existing spacecraft operating systems and packet protocols (such as AX.25) used by the Surrey Mission Operations Control Centre, and also provides basic compatibility with the industry-standard CCSDS telemetry/ telecommand (TTC) formats. Other protocols, such as TCP/IP may soon be supported.

S-Band Transmitter

The S-band transmitter (Fig. 5) is designed to operate between 2.4 and 2.5 GHz. It delivers between 100~200 mW of radio-frequency (RF) power from ~3.3 W dc. The downlink modulation scheme is nominally binary-phase-shift-keying (BPSK), but quadrature-phase-shift-keying and offset-quadrature-phase-shift-keying (OQPSK) are also supported. The nominal data rate on SNAP-1 was fixed at 38.4 kbps (BPSK), however the transmitter is actually capable of operating at data rates of up to 10 Mbps.

Fig. 5: SNAP-1 S-Band Downlink Transmitter

Two selectable scramblers are provided, "CCITT V35" and "Intelsat" standards, and differential/ Viterbi encoders are implemented in a field-programmable gate-array (FPGA). The transmitter also supports CCSDS TTC formats making SNAP-1's downlink compatible (in principle) with NASA or ESA ground-station facilities.

The S-Band transmitter contains a virtual firmware-based TTC system (implemented in its CAN-micro-controller), which is capable of poling the other spacecraft systems via the CAN bus to acquire telemetry data, before formatting and sending the data to the ground for "quick-look" health-check purposes.

Attitude and Orbit Control System (AOCS)

The Attitude and Orbit Control System (AOCS) is designed to allow 3-axis momentum-biased operation, with autonomous orbit manoeuvres.

Attitude knowledge is provided via a compact internal 3-axis flux-gate magnetometer, and a Kalman-filter attitude-estimator.

Attitude stabilisation and control is provided by a Surrey-designed miniature pitch-axis momentum wheel, running (nominally) at 2000 rpm, together with three miniature magnetorquer rods used for momentum dumping and magnetic attitude control (if required). Full details of this system are described in a companion paper [2].

A 12-Channel GPS navigation system, based on the GEC-Plessey "ORION" GPS receiver, provides accurate orbit knowledge (with ~15 m position uncertainty).

The GPS receiver and the attitude determination and control electronics are housed in a single module box (see Fig. 6).

Fig. 6: SNAP-1 Guidance, Navigation and Control Module

Cold-Gas Propulsion (CGP) System

Orbital manoeuvres are carried out via a cold-gas propulsion system (Fig. 7), which fits in the central volume of SNAP-1.

A coiled titanium pipe is used to store 32.6 g of liquefied butane propellant, which is heated and vented through a single ~50 mN thruster, to give a total theoretical velocity change of approximately 3.5 m/s. The system, and its actual performance, is described in detail a companion paper [3].

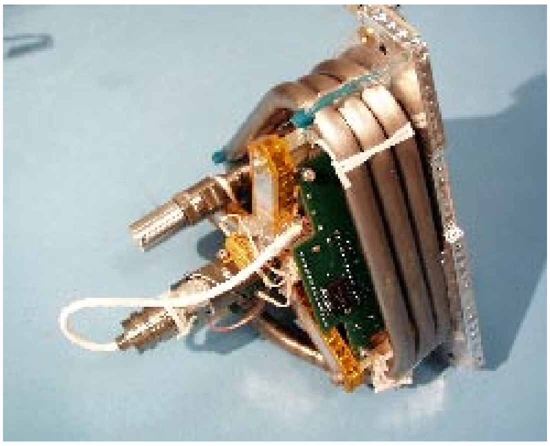

Fig. 7: SNAP-1 Butane-Based Cold-Gas Thruster

Full 3-axis stabilization (to better than 1^o in roll and yaw and 0.2^o in pitch), and extensive orbital manoeuvres have been achieved via on-board computer (OBC) control.

On-Board Computer (OBC)

The On-Board Computer (OBC) uses a 220 MHz StrongARM 32-bit SA1100 RISC processor (running nominally at 88 MHz). The 4M x 8-bit program-memory is protected by a double-bit-correcting (16,8) code implemented in hardware.

Low-level programs and a bootloader are stored in a 1M x 16-bit Flash-EPROM.

The OBC runs an SSTL-developed multi-tasking executive, and is programmed in "C".

The OBC greatly enhances the spacecraft's capabilities, providing automatic control of the spacecraft. However, as with all of our spacecraft, it is not relied upon for basic operations or the maintenance of spacecraft safety.

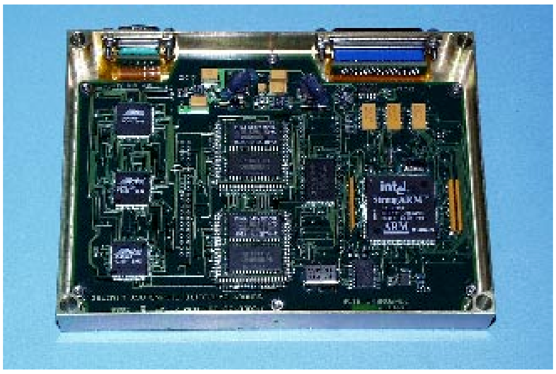

Fig. 8. SNAP-1 On-Board Computer

Mechanics

In a similar way to Surrey's micro-satellites, the SNAP-1 primary structure consists mainly of the aluminium-alloy electronics module boxes. SNAP-1 uses three stacks of three modules arranged in a triangle (see Fig.1 and Fig. 9).

The end facets of the structure are closed with aluminium honeycomb panels, and four additional honeycomb panels are used to support the solar cells.

The centre of the spacecraft provides a volume suitable to house systems which cannot be otherwise accommodated inside a stack. On SNAP-1 the propulsion system, magnetometer, momentum wheel and two of the three magnetorquer rods are located in this space.

By design, the spacecraft geometry results in each module box having three sides with a good field-of-view (FoV) to space or to the Earth. This simplifies the accommodation and integration of payloads which require external access or external sensors. We put this to good use in the machine vision system (MVS) payload, where three of the four cameras are physically mounted on the outside of the MVS module itself. Additionally it simplifies the RF harnessing, as the RF module boxes effectively act as their own bulkhead for electro-magnetic compatibility (EMC) screening.

Thermal control is passive, and is achieved via the appropriate thermo-optical tapes (first-surface and second-surface Kapton/ vacuum-deposited aluminium mirrors) being applied to the boxes and honeycomb panels.

Standard aerospace metal alloys and aluminium skinned honeycomb panels (in preference to composites) were used throughout the spacecraft. Although this results in some mass penalty, it greatly simplifies design, reduces manufacture time, and maximises the ability to deal with design changes late in the programme.

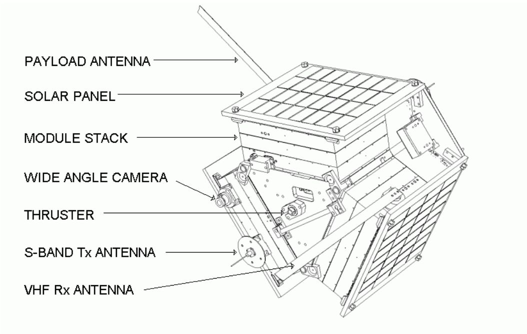

Fig. 9: SNAP-1 Spacecraft Configuration

A simple low-shock three-point separation system was also specially designed for SNAP-1 to allow it to be released into orbit from the carrying vehicle. This employed three tensioned cables to latch the spacecraft down during launch with two (redundant) pyrotechnic guillotine-cutters to release the cables for separation. A similar system could be used to release a stack of SNAP-type vehicles in a future mission requiring a multiple launch.

Payloads

Three payloads were flown on SNAP-1: a VHF spread-spectrum communications payload for a commercial customer; a UHF inter-satellite link (ISL) aimed at deriving relative position data via differential GPS to aid rendezvous manoeuvres between SNAP-1 and Tsinghua-1; and a machine vision system (MVS) for remote inspection of Tsinghua-1, imaging deployment and Earth imaging [4].

The MVS (see Fig. 10) consists of four ultra-miniature commercial-off-the-shelf CMOS video cameras (288 x 352 pixels) - three with wide-angle lenses (90^o FoV) and one with a narrow-angle lens (20^o FoV).

The lenses were standard closed-circuit TV-type lenses – stripped down and modified for use in vacuum. The narrow-angle camera had a near-infra-red filter fitted to give good differentiation between land, sea and cloud and to give a clear view through the atmosphere. The other cameras were left un-filtered to maximise sensitivity for low-light imaging.

From its 700 km altitude orbit, SNAP-1 has a ground resolution of ~500 m for the narrow angle camera and ~3 km for the wide-angle cameras.

Image storage and processing is carried out by a 220 MHz StrongARM (SA-1100) processor, which is equipped with 2 MBytes of Flash-EPROM and 8 MBytes of SRAM.

A useful additional feature of the MVS is that it can act as back-up OBC if required.

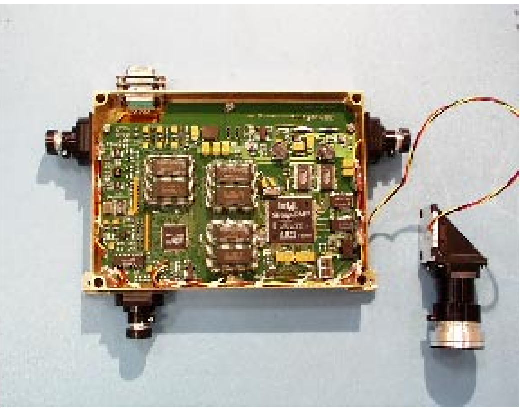

Fig. 10. SNAP-1 Machine Vision System Payload

Results

On June 28th 2000 SNAP-1, Tsinghua-1, and a Russian COSPAS-SARSAT satellite, Nadezhda, were launched from Plesetsk on a Cosmos launch vehicle into an 700 km Sun-synchronous (near polar) orbit.

The launch and early operations phase proceeded smoothly and very successfully.

The spacecraft was acquired by Surrey's Mission Control Centre on the first pass, and the data received showed that, as planned, the MVS payload had successfully acquired a sequence of images which showed the deployment of Tsinghua-1 from Nadezhda (see Fig. 11).

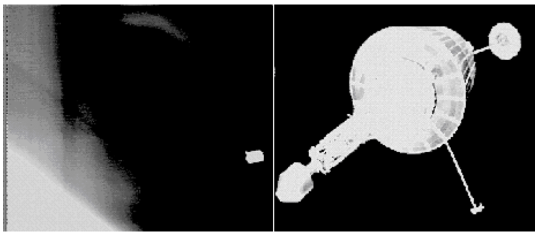

Fig. 11: (Right) Image of Nadezhda (2 seconds after separation)
(Left) Image of Tsinghua-1 and the Limb of the Earth (10 seconds after separation)

Initial data from the AOCS showed that SNAP-1 was tumbling at 26^o/s immediately after deployment (this was confirmed by analysis of the MVS images). Thus, two days after launch the automatic AOCS magnetorquer rate damping controller (built into the AOCS module firmware) was activated, and within a day this high initial rate of tumbling was completely damped and the spacecraft was placed into a slow stable, rotation about its pitch axis.

It was then discovered that, left to its own devices, SNAP-1's thruster-axis would track the Earth's magnetic field vector almost perfectly.

This was unexpected, but investigations soon determined that it was the result of small amount of residual magnetism in the propulsion system's solenoid valves. Over the course of the following months the attitude control algorithms were refined and new software uploaded to the spacecraft, so that by late November, full nadir-pointing momentum-biased operation had been achieved using the pitch-axis momentum wheel.

During this period, all the onboard systems and payloads (ISL, spread-spectrum communications and MVS) were checked and found to be working satisfactorily.

On the 15th August the propulsion system was used for the first time, and shortly afterwards orbital manoeuvres were started to try to bring SNAP-1 and Tsinghua-1 back together.

This was made difficult by the differential effects of atmospheric drag, which meant that, unless the thrusters is fired, SNAP-1 falls approximately 10m per day with respect to Tsinghua-1. This, coupled with the initial orbital insertion conditions, meant that SNAP-1 was by now some

~2 km below Tsinghua-1, and some considerable distance ahead of it. Thus, the cold-gas thruster had to be used extensively to re-gain altitude, so as to slow SNAP-1 down with respect to Tsinghua-1, in order for them to be brought back together. A long sequence of firings was initiated under the automatic control of the OBC. The GPS navigation system was used to keep track of the orbital changes.

Over the following 30 days, the thruster was fired approximately 4 times per day, giving a change in velocity (ΔV) of ~10 cm/s per day, by which time SNAP-1 had climbed ~1 km above Tsinghua-1.

High solar activity (and hence marked differential drag) meant that a further sequence of firings was necessary to have any chance of completing a rendezvous, and unfortunately the propellant ran out during this second firing sequence.

In total, taking atmospheric drag effects into account, the propulsion system raised the altitude of SNAP-1 by the equivalent of ~4 km (with a corresponding total ΔV of 2.1 m/s) – all done using just 32.6 g of butane propellant.

At maximum separation, Tsinghua-1 and SNAP-1 were approximately 15,000 km apart. By means of these manoeuvres, SNAP-1 passed Tsinghua-1's orbital altitude on 18th March 2001, at a minimum separation distance of approximately 2000 km. Thus, whilst true rendezvous was not achieved, the agility and manoeuvrability of SNAP-1 under automatic control was amply demonstrated.

As well as providing the commercial communications payload, SNAP-1 continues to be used to investigate new attitude control techniques, and to study the effects of atmospheric drag on such a low-mass spacecraft.

The MVS payload is also currently being used to acquire images and movie-sequences of the Earth under differing lighting conditions (Fig. 12).

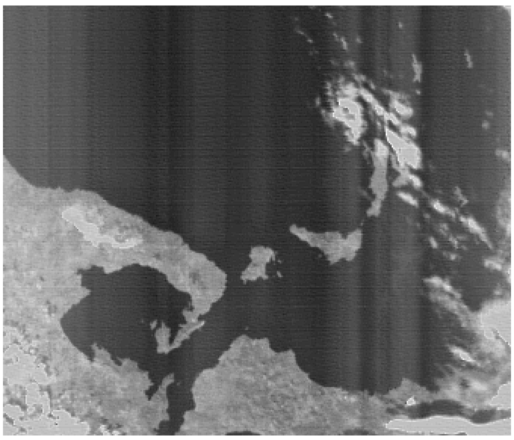

Fig. 12: Greek Islands Imaged by SNAP-1 MVS Narrow-Angle Camera on 31/3/01

The Future

The SNAP concept provides an effective off-the-shelf solution for the provision of low-cost flight-proven satellite systems. Indeed, the success of the SNAP-1 mission has already lead to United States Air Force Academy (USAFA) adopting SNAP modules for its own educational nano-satellite programme: FalconSAT-2. In this way, they have been able to leverage off the SNAP experience to gain a ready-made spacecraft architecture, allowing the programme to concentrate on other issues (e.g. payloads). Thus, the SNAP core modules (Power, OBC, RF, etc.) have become complete COTS spacecraft systems!

Surrey Space Centre and USAFA are working closely on the development of educational programmes based on SNAP.

At SSTL, a number of missions are being planned around the SNAP architecture, and the lessons learnt, particularly from the on-orbit operations of SNAP-1's propulsion system, have proved invaluable for the design of SSTL's forthcoming satellite constellation missions such as the Disaster Monitoring Constellation (DMC).

Conclusions

The SNAP-1 mission has been highly successful, and has met its purpose of demonstrating that low-cost (less than £1M mission cost), modular, COTS-based nano-satellites can be constructed rapidly (in less than 9 months) to achieve sophisticated mission objectives.

Acknowledgments

The authors wish to thank all at SSC/SSTL who have contributed, and continue to contribute to the success of the SNAP mission.

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